SYSTEM AND METHOD FOR DESENSITIZING THE ACTIVATION CRITERIA OF A ROLLOVER CONTROL SYSTEM

RELATED APPLICATIONS

The present invention claims priority to U.S. provisional applications serial number 60/401,464 and 60/401,416, filed August 5, 2002, the disclosures of which are incorporated by reference herein. The present application is also related to U.S. Application (Attorney Docket No. 202-0923/FGT-1692) entitled "SYSTEM AND METHOD FOR SENSITIZING THE ACTIVATION CRITERIA OF A ROLLOVER CONTROL SYSTEM", filed simultaneously herewith.

TECHNICAL FIELD

[0001]   The present invention relates generally to a control apparatus for controlling a system of an automotive vehicle in response to sensed dynamic behavior, and more specifically, to a method and apparatus for desensitizing the activation criteria based on vehicle operating conditions.

BACKGROUND

[0002]   Dynamic control systems for automotive vehicles have recently begun to be offered on various products. Dynamic control systems typically control the yaw of the vehicle by controlling the braking effort at the various wheels of the vehicle. Yaw control systems typically compare the desired direction of the vehicle based upon the steering wheel angle and the direction of travel. By regulating the

amount of braking at each corner of the vehicle, the desired direction of travel may be maintained. Typically, the dynamic control systems do not address rollover (wheels lifting) of the vehicle. For high profile vehicles in particular, it would be desirable to control the rollover characteristic of the vehicle to maintain the vehicle position with respect to the road. That is, it is desirable to maintain contact of each of the four tires of the vehicle on the road.

[0003] In vehicle rollover control, it is desired to alter the vehicle attitude such that its motion along the roll direction is prevented from achieving a predetermined limit (rollover limit) with the aid of the actuation from the available active systems such as controllable brake system, steering system and suspension system. Although the vehicle attitude is well defined, direct measurement is usually impossible.

[0004] During a potential vehicular rollover event, wheels on one side of the vehicle start lifting, and the roll center of the vehicle shifts to the contact patch of the remaining tires. This shifted roll center increases the roll moment of inertia of the vehicle, and hence reduces the roll acceleration of the vehicle. However, the roll attitude could still increase rapidly. The corresponding roll motion when the vehicle starts side lifting deviates from the roll motion during normal driving conditions.

[0005] When the wheels start to lift from the pavement, it is desirable to confirm this condition. This allows the system to make an accurate

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determination as to the appropriate correction. If wheels are on the ground, or recontact the ground after a lift condition, this also assists with accurate control.

[0006] Some systems use position sensors to measure the relative distance between the vehicle body and the vehicle suspension. One drawback to such systems is that the distance from the body to the road must be inferred. This also increases the number of sensors on the vehicle. Other techniques use sensor signals to indirectly detect wheel lifting qualitatively.

[0007] One example of a wheel lifting determination can be found in Ford patent U.S. 6,356,188 and U.S. patent application (Attorney Docket 202-0433/FGT-1683 PA), both of which are incorporated by reference herein. The system applies a change in torque to the wheels to determine wheel lift. The output from such a wheel lifting determination unit can be used qualitatively. This method is an active determination since the basis of the system relies on changing the torque of the wheels by the application of brakes or the like. In some situations it may be desirable to determine wheel lift without changing the torque of a wheel.

[0008] Due to the inevitable dead spots due to the vehicle configuration, wheel lift detection methods may not be able to identify all the conditions where four wheels are absolutely grounded in a timely and accurate fashion. For example, if the torques applied to the wheels have errors, if the vehicle reference computation has errors or there is not enough

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excitation in the torque provided, the wheel lift detection may provide erroneous information or no information about the roll trending of the vehicle. Wheel lift information may also be safe-guarded by information regarding the vehicle roll angle information from the various sensors.

[0009]   In certain driving conditions where the vehicle is moving with all four wheels contacting ground and the wheel lift detection does not detect the grounding condition, the roll information derived from the various sensors may be the sole information for identify vehicle roll trending.   If in such driving cases, the vehicle experiences very large lateral acceleration and large roll rate, the grounded conditions might be replaced by erroneous lifting conditions.   That is, those signals may predict that the vehicle is in a divergent roll event but the actual vehicle is not in a rolling event at all.   Such cases include when the vehicle is driven on a mountain road, off-road or banked road, tire compression or an impact may cause a large normal load.   The increased normal load causes a force component to be added to the lateral acceleration sensor output.   Hence, a larger than 1 g lateral acceleration is obtained but the actual lateral acceleration of the vehicle projected along the road surface might be in 0.6 g range.   An off-road driving condition may also be an off-camber driving condition.   When a low speed vehicle is driven on an off-camber road with some hard tire compression or impact, the control system may be fooled to activate un-necessarily.

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[0010] In order to reduce false activations, it would therefore be desirable to provide a rollover detection system that sensitizes and desensitizes the roll control determination.

SUMMARY

[0011] The present invention sensitizes and desensitizes the roll decision based upon various conditions to make the roll decision more accurate.

[0012] In one embodiment, a method of densensitizing includes determining a relative roll angle, determining when the vehicle is in a transitional maneuver, and when the vehicle is in a transitional maneuver, setting a roll signal for control to the relative roll angle, reducing control effort and controlling a safety system correspondingly.

[0013] In another embodiment, a method of operating a vehicle comprises determining roll condition, holding a peak brake pressure to counteract rollover, determining a first wheel departure angle, determining a second wheel departure angle after the first wheel departure angle, and when the change of the first wheel departure angle and the second wheel departure angle is less than a threshold, releasing the peak brake pressure.

[0014] One advantage of the invention is that some or all of the ways in which to sensitize and desensitize may be used alone or simultaneously to improve a safety system such as a rollover control system.

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[0015] Other advantages and features of the present invention will become apparent when viewed in light of the detailed description of the preferred embodiment when taken in conjunction with the attached drawings and appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] Figure 1 is a diagrammatic view of a vehicle with variable vectors and coordinator frames.

[0017] Figure 2 is an end view of an automotive vehicle on a bank with definitions of various angles including global roll angle, relative roll angle, wheel departure angle (WDA), road bank angle and body-to-road angle.

[0018] Figure 3A is an end view of an on-camber divergent vehicle tendency.

[0019] Figure 3B is an end view of an automotive vehicle in an off-camber divergent condition.

[0020] Figure 3C is an end view of a vehicle in an on-camber convergent condition.

[0021] Figure 3D is an end view of a vehicle in an off-camber convergent condition.

[0022] Figure 4A is a block diagram of a stability control system.

[0023] Figure 4B is a block diagram of the controller 26 used in the stability control system depicted in Figure 4A.

[0024]   Figure 5 is a block diagrammatic view of the unit 27 depicted in Figure 4B, which is used for quantitatively and qualitatively determining rollover trend of a vehicle.

[0025]   Figure 6 is more detailed view of the sensitizing and desensitizing block of Figure 5.

[0026]   Figure 7 is a plot of wheel departure angle versus time for normal conditions and for those of the present embodiment.

[0027]   Figure 8 is flow chart of the operation of one embodiment of sensitizing according to one embodiment of the present invention.

[0028]   Figure 9 is flow chart of the operation of one embodiment of desensitizing according to one embodiment of the present invention.

[0029]   Figure 10 is a flow chart illustrating exiting a proportional peak hold strategy.

[0030]   Figure 11 is a flow chart illustrating the timing of active wheel lift detection.

DETAILED DESCRIPTION

[0031]   In the following figures the same reference numerals will be used to identify the same components. The present teachings may be used in conjunction with a yaw control system or a rollover control system for an automotive vehicle. However, the present teachings may also be used with a deployment device such as airbag or roll bar.

[0032]   Referring to Figure 1, an automotive vehicle
10 on a road surface 11 with a safety system is
illustrated with the various forces and moments
thereon. Vehicle 10 has front right and front left
tires 12a and 12b and rear right tires and rear left
tires 13a and 13b, respectively. The vehicle 10 may
also have a number of different types of front
steering systems 14a and rear steering systems 14b
including having each of the front and rear wheels
configured with a respective controllable actuator,
the front and rear wheels having a conventional type
system in which both of the front wheels are
controlled together and both of the rear wheels are
controlled together, a system having conventional
front steering and independently controllable rear
steering for each of the wheels, or vice versa.
Generally, the vehicle has a weight represented as Mg
at the center of gravity of the vehicle, where
$g = 9.8\, m/s^2$ and M is the total mass of the vehicle.

[0033]   As mentioned above, the system may also be
used with active/semi-active suspension systems, anti-
roll bar or other safety devices deployed or activated
upon sensing predetermined dynamic conditions of the
vehicle.

[0034]   The sensing system 16 is part of a control
system 18. The sensing system 16 may use a standard
yaw stability control sensor set (including lateral
acceleration sensor, yaw rate sensor, steering angle
sensor and wheel speed sensor) together with a roll
rate sensor and a longitudinal acceleration sensor.
The various sensors will be further described below.

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The wheel speed sensors 20 are mounted at each corner of the vehicle, and the rest of the sensors of sensing system 16 may be mounted directly on the center of gravity of the vehicle body, along the directions x, y and z shown in Figure 1. As those skilled in the art will recognize, the frame from b_1, b_2 and b_3 is called a body frame 22, whose origin is located at the center of gravity of the car body, with the b_1 corresponding to the x axis pointing forward, b_2 corresponding to the y axis pointing off the driving side (to the left), and the b_3 corresponding to the z axis pointing upward. The angular rates of the car body are denoted about their respective axes as ω_x for the roll rate, ω_y for the pitch rate and ω_z for the yaw rate. The calculations set forth herein may take place in an inertial frame 24 that may be derived from the body frame 22 as described below.

[0035] The angular rate sensors and the acceleration sensors are mounted on the vehicle car body along the body frame directions b_1, b_2 and b_3, which are the $x-y-z$ axes of the vehicle's sprung mass.

[0036] The longitudinal acceleration sensor 36 is mounted on the car body located at the center of gravity, with its sensing direction along b_1-axis, whose output is denoted as a_x. The lateral acceleration sensor 32 is mounted on the car body located at the center of gravity, with its sensing

direction along b_2-axis, whose output is denoted as a_y.

[0037]   The other frame used in the following discussion includes the road frame, as depicted in Figure 1.   The road frame system $r_1 r_2 r_3$ is fixed on the driven road surface, where the r_3 axis is along the average road normal direction computed from the normal directions of the four-tire/road contact patches.

[0038]   In the following discussion, the Euler angles of the body frame $b_1 b_2 b_3$ with respect to the road frame $r_1 r_2 r_3$ are denoted as $\theta_{xr,} \theta_{yr}$ and θ_{zr}, which are also called the relative Euler angles.

[0039]   Referring now to Figure 2, the relationship of the various angles of the vehicle 10 relative to the road surface 11 is illustrated.   One angle is a wheel departure angle θ_{wda}, which is the angle from the axle or the wheel axis to the road surface 11.   Also shown is a reference road bank angle θ_{bank}, which is shown relative to the vehicle 10 on a road surface. The vehicle 10 has a vehicle body 10a and vehicle suspension 10b.   The relative roll angle θ_{xr} is the angle between the wheel axle and the body 10a.   The global roll angle θ_x is the angle between the horizontal plane (e.g., at sea level) and the vehicle body 10a.

[0040]   Referring now to Figure 3A, vehicle 10 is illustrated in an on-camber divergent state.   The on-

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camber divergent state refers to the vehicle having a greater than zero wheel departure angle, a greater than zero relative roll angle, and a moment represented by arrow 25 tending to increase the relative roll angle and the wheel departure angle. In this example, the bank angle is less than zero.

[0041]   In Figure 3B, when the bank angle is greater than zero, the wheel departure angle is greater than zero, the relative roll angle is greater than zero and the moment is also to the right or increasing the relative roll angle and the wheel departure angle, the vehicle is in an off-camber divergent state.

[0042]   Referring now to Figure 3C, a bank angle of less than zero, a wheel departure angle greater than zero, and a relative roll angle greater than zero is shown with a roll moment 25 acting to the left. Thus, the vehicle is in an on-camber convergent state. That is, the convergent state refers to the vehicle tending towards not overturning.

[0043]   Referring now to Figure 3D, when the bank angle is greater than 0, the wheel departure angle is greater than zero, and the relative roll angle is greater than zero and the roll moment is tending to the left, the vehicle is in an off-camber convergent state. That is, the vehicle is tending toward not rolling over.

[0044]   Referring now to Figure 4A, one embodiment of a roll stability control system 18 is illustrated in further detail having a controller 26 used for receiving information from a number of sensors which

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may include a yaw rate sensor 28, a speed sensor 20, a lateral acceleration sensor 32, a roll rate sensor 34, a steering angle sensor (hand wheel position) 35, a longitudinal acceleration sensor 36, and steering angle position sensor 37.

[0045]   In one embodiment, the sensors are located at the center of gravity of the vehicle.   Those skilled in the art will recognize that the sensors may also be located off the center of gravity and translated equivalently thereto.

[0046]   Lateral acceleration, roll orientation and speed may be obtained using a global positioning system (GPS).   Based upon inputs from the sensors, controller 26 may control a safety device 38. Depending on the desired sensitivity of the system and various other factors, not all the sensors 20, 28, 32, 34, 35, 36, and 37, or various combinations of the sensors, may be used in a commercial embodiment. Safety device 38 may control an airbag 40, an active braking system 41, an active front steering system 42, an active rear steering system 43, an active suspension system 44, and an active anti-roll bar system 45, or combinations thereof.   Each of the systems 40-45 may have their own controllers for activating each one.   As mentioned above, the safety system 38 may be at least the active braking system 41.

[0047]   Roll rate sensor 34 may sense the roll condition of the vehicle based on sensing the height of one or more points on the vehicle relative to the road surface.   Sensors that may be used to achieve

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this include a radar-based proximity sensor, a laser-based proximity sensor and a sonar-based proximity sensor.

[0048]   Roll rate sensor 34 may also sense the roll condition based on sensing the linear or rotational relative displacement or displacement velocity of one or more of the suspension chassis components which may include a linear height or travel sensor, a rotary height or travel sensor, a wheel speed sensor used to look for a change in velocity, a steering wheel position sensor, a steering wheel velocity sensor and a driver heading command input from an electronic component that may include steer by wire using a hand wheel or joy stick.

[0049]   The roll condition may also be sensed by sensing the force or torque associated with the loading condition of one or more suspension or chassis components including a pressure transducer in active air suspension, a shock absorber sensor such as a load cell, a strain gauge, the steering system absolute or relative motor load, the steering system pressure of the hydraulic lines, a tire lateral force sensor or sensors, a longitudinal tire force sensor, a vertical tire force sensor or a tire sidewall torsion sensor.

[0050]   The roll condition of the vehicle may also be established by one or more of the following translational or rotational positions, velocities or accelerations of the vehicle including a roll gyro, the roll rate sensor 34, the yaw rate sensor 28, the lateral acceleration sensor 32, a vertical acceleration sensor, a vehicle longitudinal

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acceleration sensor, lateral or vertical speed sensor including a wheel-based speed sensor, a radar-based speed sensor, a sonar-based speed sensor, a laser-based speed sensor or an optical-based speed sensor.

[0051]   Based on the inputs from sensors 20, 28, 32, 34, 35, 36, 37, controller 26 determines a roll condition and controls any one or more of the safety devices 40-45.

[0052]   Speed sensor 20 may be one of a variety of speed sensors known to those skilled in the art. For example, a suitable speed sensor 20 may include a sensor at every wheel that is averaged by controller 26. The controller 26 translates the wheel speeds into the speed of the vehicle. Yaw rate, steering angle, wheel speed and possibly a slip angle estimate at each wheel may be translated back to the speed of the vehicle at the center of gravity. Various other algorithms are known to those skilled in the art. For example, if speed is determined while speeding up or braking around a corner, the lowest or highest wheel speed may not be used because of its error. Also, a transmission sensor may be used to determine vehicle speed.

[0053]   Referring now to Figures 4A and 4B, controller 26 is illustrated in further detail. There are two major functions in controller 26:   the rollover trend determination, which is called a sensor fusion unit 27A, and the feedback control command unit 27B. The sensor fusion unit 27A can be further decomposed as a wheel lift detector 50, a transition detector 52 and a vehicle roll angle calculator 66.

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[0054]   Referring now to Figure 5, the sensor fusion unit 27A is illustrated in further detail. The sensor fusion unit 27A receives the various sensor signals, 20, 28, 32, 34, 35, 36, 37 and integrates all the sensor signals with the calculated signals to generate signals   suitable   for   roll   stability   control algorithms.   From the various sensor signals wheel lift detection may be determined by the wheel lift detector 50.   Wheel lift detector 50 includes both active wheel lift detection and passive wheel lift detection, and wheel grounding condition detection. Wheel lift detector is described in co-pending U.S. provisional application serial number 60/400,375 (Attorney Docket 202-0433/FGT-1683PRV) filed August 1, 2002, and U.S. patent application (Attorney Docket 202-0433/FGT-1683PA),   which   are   incorporated   by reference herein. The modules described below may be implemented in hardware or software in a general purpose computer (microprocessor).   From the wheel lift detection module 50, a determination of whether each wheel is absolutely grounded, possibly grounded, possibly lifted,   or absolutely lifted may be determined. Transition detection module 52 is used to detect whether the vehicle is experiencing aggressive maneuver due to sudden steering wheel inputs from the driver.   The sensors may also be used to determine a relative roll angle in relative roll angle module 54. Relative roll angle may be determined in many ways. One way is to use the roll acceleration module 58 in conjunction with the lateral acceleration sensor.   As described above, the relative roll angle may be determined from the roll conditions described above.

[0055]   The various sensor signals may also be used to determine a relative pitch angle in relative pitch angle module 56 and a roll acceleration in roll acceleration module 58.   The outputs of the wheel lift detection module 50, the transition detection module 52, and the relative roll angle module 54 are used to determine a wheel departure angle in wheel departure angle module 60.   Various sensor signals and the relative pitch angle in relative pitch angle module 56 are used to determine a relative velocity total in module 62.   The road reference bank angle block 64 determines the bank angle.   The relative pitch angle, the roll acceleration, and various other sensor signals as described below are used to determine the road reference bank angle.   Other inputs may include a roll stability control event (RSC) and/or the presence of a recent yaw stability control event, and the wheel lifting and/or grounding flags.

[0056]   The global roll angle of the vehicle is determined in global roll angle module 66.   The relative roll angle, the wheel departure angle, and the roll velocity total blocks are all inputs to the global roll angle total module 66.   The global roll angle total block determines the global roll angle θ_x.   An output module 68 receives the global roll angle total module 66 and the road reference bank angle from the road reference bank angle module 64.   A roll signal for control is developed in roll signal module 70.   The roll signal for control is illustrated as arrow 72.   A sensitizing and desensitizing module 74

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may also be included in the output module 68 to adjust the roll signal for control.

[0057]   In the reference road bank angle module 64, the reference bank angle estimate is calculated.   The objective of the reference bank estimate is to track a robust but rough indication of the road bank angle experienced during driving in both stable and highly dynamic situations, and which is in favor for roll stability control.   That is, this reference bank angle is adjusted based on the vehicle driving condition and the vehicle roll condition.   Most importantly, when compared to the global roll estimate, it is intended to capture the occurrence and physical magnitude of a divergent roll condition (two wheel lift) should it occur.   This signal is intended to be used as a comparator against the global roll estimate for calculating the error signal, which is fed back to roll stability controller 26.

[0058]   Referring now to Figure 6, the operation of the sensitizing/desensitizing module 74 is described in further detail.   In this module, the needed control effort used in the roll stability control RSC system is sensitized by deliberately increasing certain thresholds, boosting certain signals and holding certain variables in order to cope with scenarios where the vehicle is in divergent roll trend; the control effort used in RSC is desensitized by deliberately decreasing certain thresholds, exiting holding mode and inserting hysteresis in certain variables in order to cope with the scenarios where the vehicle is not in divergent roll trend but the

vehicle sensors cannot distinguish such no-divergent roll trend with the divergent or unstable dynamics. In summary, the sensitization is used to boost the control effort in the side of the vehicle needed, and desensitization is used to detune the control effort in the un-needed side so as to reduce false activations in non-rollover events.

[0059] The module has various external inputs that include a relative roll angle θ_{xr} input 80; a roll signal for control θ_{rsfc} input 82; a roll rate ω_x input 84; a wheel departure angle θ_{wda} input 86, a first transitional flag input 88 for left to right transition denoted as $T(0)$ and a second transitional flag 90 denoted as $T(1)$ for right to left transition. The transitional flags are set as the vehicle change from a right to left turn and a left to right turn. The generation of the transitional flags is described in provisional application 60/401,416 which is incorporated by reference herein. Other inputs include a final wheel lift status flags input 92 that is denoted by $S_{wld}(i)$. The final wheel lift status flag is set so:

[0060] If the ith wheel is absolutely grounded, then $S_{wld}(i) = ABSOLUTELY\_GROUNDED$

- If the ith wheel is in the edge of grounding, $S_{wld}(i) = POSSIBLY\_GROUNDED$
- If the ith wheel is absolutely lifted, then $S_{wld}(i) = ABSOLUTELY\_LIFTED$
- If the ith wheel is in the edge of lifting $S_{wld}(i) = POSSIBLY\_LIFTED$

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- If the ith wheel's status cannot be firmly identified, $S_{wld}(i) = NO\_INDICATION$

[0061]   Other inputs include a reference bank angle input 94 denoted as $\theta_{refbank}$ and a global roll angle input 96 θ_x

[0062]   The outputs of the module 74 include a wheel departure angle output 98 denoted by θ_{wda}, a roll signal for control output 100 denoted by θ_{rsfc}, a proper-peak-hold flag output 102 denoted by F_{PPH}, a reference bank angle output 104 denoted $\theta_{refbank}$ and a pre-lift sensing flag output 106 denoted by F_{PLS}.

PREDEFINED CALIBRATABLE PARAMETER DEFINITIONS

[0063]   The module 74 also includes various parameters and thresholds that are defined as follows:

$\Theta_{sensitize}$: the threshold for the relative roll angle used for sensitizing wheel departure angle during transitional maneuvers. Default value used in the present example = 45% of roll gradient.

α : percentage of relative roll angle boosted for roll signal for control during double wheel lift events.

$\Theta_{wheel-normal-condition}$: the threshold for the relative roll angle for starting the computation of the wheel departure angle during normal driving condition.   Default value used in the present example = 75% of the roll gradient.

$\Theta_{non-transition}$: the threshold for the relative roll angle used in starting to adjust the reference

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bank during non-transitional maneuvers. Default value used in the present example = 80% of roll gradient.

$\Delta\Theta$: the threshold for wheel departure angle drop during to sequential loops used for exiting proportional peak hold mode in PID controller. Default value used in the present example = 4 degree.

Ω_{PPH}: threshold for the roll angular rate in order to enter proportional peak hold mode. Default value = used in the present example 16 degree per second.

Θ_{PLS}: the threshold for the wheel departure angle in order to start the pre-lift sensing. Default value used in the present example = 1 degree.

T: the threshold for the drive torque at a wheel to start the pre-lift sensing.

Sensitization

[0064] Referring now to figure 7, the starting point of computing the wheel departure angle is assumed to be at the time instant where one of the tires is at the edge of losing its normal load, or at the edge of being lifted. The exact time, however, is not typically detectable. Considering all the uncertainties in a vehicle, the approximated timing may be identified based on the wheel lift detection and the vehicle roll information. As shown in Figure 7, the time instant where the tire is about to lift is illustrated as t_0, then before t_0 at time t_{01}, the wheel departure angle must have negative value. The wheel departure angle is reset to zero when the computation start. Thus if the computation is started at a time instant earlier than t_0, the negative wheel departure angle due to tire compression (usually around 1

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degree) will be added to the computed wheel departure angle to effectively boost the wheel departure angle. This sensitizes the wheel departure angle. If the start timing for computing wheel departure angle is later than t_0 at time t_{02}, the magnitude of the calculated wheel departure angle will be less than the magnitude of the actual value, hence desensitizes the wheel departure angle.

[0065]   Referring now to Figure 8, if the vehicle is near wheel lifting in step 120, in step 122 the transitional flags are monitored. The vehicle left to right transitional or right to left transitional flags are set to be active due to a dynamic transitional maneuver of the vehicle. In such a case, the vehicle may have a very large roll rate and hence a high roll trend. In this case any late computation of the wheel departure will desensitize the control effort which will have adverse control effect. Hence in this case the wheel departure angle computation is sensitized such that a needed control effort can be boosted.

$$\text{if } (\ (T(0) = 1 \ \&\& \ \theta_{xr} \ \geq \ \Theta_{sensitize})$$
$$\| \ (T(1) == 1 \ \&\& \ \theta_{xr} \ \leq \ - \Theta_{sensitize})$$

{

    Compute wheel departure angle;

}

else if the normal conditions are met

{

    Exit computing wheel departure angle;

}

[0066]   The relative roll angle is determined in step 124. Notice that if the normal condition for

computing wheel departure starts at a relative roll magnitude Θ_{normal}, then the threshold $\Theta_{sensitize}$ for sensitizing wheel departure angle during transitional maneuver could be as small as 50% of Θ_{normal}. In step 126 the transitional flags are monitored and the relative roll angle θ_{xr} exceeds or is equal to the sensitizing threshold and the left to right transition flag is set or the right to left transition flag is set and the relative roll angle θ_{xr} is less than or equal to a negative $\Theta_{sensitize}$ threshold. The boosted wheel departure angle is obtained by starting the calculation earlier than at a nominal time t_0 as described above in step 128. The boosted wheel departure angle will add certain amount of roll angle to the final roll signal for control θ_{rsfc}, hence help increase certain amount of control effort.

[0067]   If the wheel lift detection methods identify that two wheels at the inside of a turn are both lifted in step 130, then the vehicle is in a progressive rollover event. In this case significant control effort is required in order to fully control the vehicle body such that rollover can be prevented. One sensitizing method is to further boost the roll signal for control as in step 132 as set forth in the following:

$$
\begin{aligned}
&if\,((S_{wld}(0) == 1\,\&\,\&S_{wld}(2) == 1\,\&\,\&\theta_{xr} > 0) \\
&\quad \|\,(S_{wld}(1) == 1\,\&\,\&S_{wld}(3) == 1\,\&\,\&\theta_{xr} \le 0)) \\
&\{ \\
&\quad \theta_{rsfc} = \theta_{rsfc} + \alpha\% * \theta_{xr}; \\
&\}
\end{aligned}
$$

where α is the percentage of the desired boost. The default value in this example is 10.

[0068] In step 134 whether the vehicle is bouncing is determined. When the vehicle has very large roll angle together with a large magnitude of the roll rate during last second, the vehicle will be in a potential bouncing mode. In this case a proportional peak hold of the brake pressure (roll control effort) is conducted. A proportional control term is calculated in:

$$if \text{ (vehicle is in bouncing mode)}$$
$$\{$$
$$\text{Proportianl\_control\_term} = K_p \theta_{rsfc-peak}$$
$$\}$$
$$else$$
$$\{$$
$$\text{Proportianl\_control\_term} = K_p \theta_{rsfc}$$
$$\}$$

where $\theta_{rsfc-peak}$ is the peak value of the roll signal for control during a specific period of time in step 136.

Desensitization

[0069] Referring now to Figure 9, as mentioned above it may also be desirable to desensitize the system in certain situations. For example, during a transitional maneuver, the roll signal for control θ_{rsfc} will be reduced to relative roll angle θ_{xr} if the wheel lift detection algorithms identify that the two wheel at the inside of a turn are absolutely grounded. In this case, the vehicle is not in any roll divergence and the roll angle between the vehicle body and the

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road surface is exactly the relative roll angle θ_{xr}. Since usually θ_{xr} alone will not be able to initiate PID control, hence resetting θ_{rsfc} to θ_{xr} will exit RSC control. This is set forth in step 140 by first determining if the vehicle is in a transitional maneuver. If the inside wheels are absolutely grounded in step 142 (and there is some roll angle in the right direction) then the roll signal for control is set to the relative roll angle in step 144.

$$
\begin{aligned}
if(\quad &(T(0) == 1 \\
&\&\&S_{wld}(1) == ABSOLUTELY\_GROUNDED \\
&\&\&S_{wld}(3) == ABSOLUTELY\_GROUNDED \\
&\&\&\theta_{xr} \le 0) \\
&(T(1) == 1 \\
&\&\&S_{wld}(0) == ABSOLUTELY\_GROUNDED \\
&\&\&S_{wld}(2) == ABSOLUTELY\_GROUNDED \\
&\&\&\theta_{xr} > 0) \quad) \\
&\{ \\
&\quad \theta_{rsfc} = \theta_{xr} + \theta_{wda} = \theta_{xr}; \\
&\}
\end{aligned}
$$

[0070] During non-transitional maneuver, the roll signal for control θ_{rsfc} will be reduced to relative roll angle θ_{xr} if the wheel lift detection algorithms identify that one of the two inside wheels at a turn is absolutely grounded. In this case, the vehicle is not in any roll divergence and the roll angle between the vehicle body and the road surface is exactly the relative roll angle θ_{xr}. Since usually θ_{xr} alone will not be able to initiate PID control, hence resetting θ_{rsfc} to θ_{xr} will exit RSC control. This is carried out

in step 140 when there is no transitional maneuver. In step 146 whether one of two inside wheels is grounded is determined. If one of the two inside wheels are grounded, step 144 is again executed in which the roll signal for control is set to the relative roll angle. This is set forth in the following code.

$$
\begin{aligned}
&if(\quad (T(0) == 0 \\
&\qquad \&\&(S_{wld}(1) == ABSOLUTELY\_GROUNDED \\
&\qquad\qquad || S_{wld}(3) == ABSOLUTELY\_GROUNDED) \\
&\qquad \&\&\theta_{xr} \leq 0) \\
&\qquad (T(1) == 0 \\
&\qquad \&\&(S_{wld}(0) == ABSOLUTELY\_GROUNDED \\
&\qquad\qquad || S_{wld}(2) == ABSOLUTELY\_GROUNDED) \\
&\qquad \&\&\theta_{xr} > 0)\quad) \\
&\{ \\
&\qquad \theta_{rsfc} = \theta_{xr} + \theta_{wda} = \theta_{xr}; \\
&\}
\end{aligned}
$$

[0071]   In non-transitional maneuver, the reference bank is updated when the magnitude of the relative roll angle is less than a $\Theta_{non-transition}$ threshold, which is larger than the $\Theta_{wda-normal-condition}$ threshold in step 148. Hence there is a gap of the relative roll angle which is used to provide certain hysteresis in reference bank angle computation. If the magnitude of the relative roll angle is under the $\Theta_{non-transition}$ threshold but greater than $\Theta_{wda-normal-condition}$, even wheel departure angle is already starting to be computed, the reference bank angle will wait until the relative roll angle exceeds $\Theta_{non-transition}$ threshold to be

adjusted, and hence the roll signal for control to be adjusted. That is, the reference road bank θ_{ref} is set to the maximum of the global roll angle $\theta_x - \theta_{xss}$ or the previously determined reference bank angle. This is set forth in the following code:

$$if \ ((\ \ \theta_{xr} \ < \ -\Theta_{non\text{-}transition}$$
$$\&\& \ (\ S_{wld}(1) != ABSOLUTELY\_GROUNDED$$
$$\| \ S_{wld}(3) \ != ABSOLUTELY\_GROUNDED \ ) \ )$$
$$\| \ (\ \ \theta_{xr} \ \geq \Theta_{non\text{-}transition}$$
$$\&\& \ (\ S_{wld}(0) != ABSOLUTELY\_GROUNDED$$
$$\| \ S_{wld}(2) \ != ABSOLUTELY\_GROUNDED \ ) \ )$$
$$\{$$
$$\theta_{ref\text{-}bank} = \ max(\ \theta_x \ - \ \theta_{xss}, \theta_{ref\text{-}bank});$$
$$\}$$

where $\theta_{xss} = \theta_x - \theta_{xr} - \theta_{wda}$.

[0072] Referring now to Figure 10, in step 162 if the incremental correction for the wheel departure angle for two sequential loops exceeds certain magnitude $\Delta\Theta$ (default value = 4 degree), the RSC will exit proportional peak brake pressure holding by resetting the flag F_{PPH} to zero in step 164. In step 162 the previous wheel departure angle is subtracted from a current wheel departure angle. In this case, the self adjusting feature of the wheel departure angle computation implies that the vehicle is not in a divergent roll motion, hence holding brake pressure will cause the driver an un-easy feeling. Exiting enforced proportional peak hold pressure will allow the roll information of the vehicle to set the control effort to appropriate level.

$$if \ (|\,\theta_{wda}(k) - \theta_{wda}(k-1)\,| > \Delta\Theta)$$
$$\{$$
$$\qquad F_{PPH} = 0;$$
$$\}$$

where $\theta_{wda}(k)$ denotes the current value of the wheel departure angle and $\theta_{wda}(k-1)$ denotes the past value of the wheel departure angle.

[0073]   In step 166, if the vehicle roll rate does not exceed a threshold Ω_{PPH} (16 degree/sec in the present example) within last 1 second, the vehicle is identified as not in the bouncing mode.   Hence proportional peak hold will be ended in step 164.   In this case, there is no need to hold brake pressure. Exiting enforced proportional peak hold pressure will allow the roll information of the vehicle to set the control effort to appropriate level.

$$if \ (|\,\omega_x\,| \ < \ \Omega_{PPH} \quad during \ last \ 1 \ second)$$
$$\{$$
$$\qquad F_{PPH} = 0;$$
$$\}$$

[0074]   Referring now to Figure 11, it may be desirable to start active wheel lift detection early. Although the passive wheel lift detection is performed all the time, the active wheel lift detection is conditionally performed.   For example, only if the RSC enters PID control mode the active wheel lift detection is activated.   Since the PID control is related to roll trend conditioned by the wheel lifting information and there is a delay between the beginning

of the active detection and the time when the detection resets the flag, there may be cases where a long lasting un-necessary activation from the PID controller is performed. The active wheel lift detection may thus be performed before the PID controller is activated. The delay due to the active wheel lift detection consequently may be removed. This implies the need for an earlier active wheel lift detection, which may be called pre-lift sensing. That is before entering the PID control mode and the transitional control mode, the active wheel lift detection will start to proceed under certain conditions. One of the conditions is dependent on the wheel departure angle. If the wheel departure angle is greater than certain threshold and the driving torque at the axle is below certain threshold in step 170, a prelifting flag is set in step 172, the active wheel lift detection will request engine torque reduction or provide a pressure command to the wheel in step 174. In this manner, un-necessary false activations can be avoided or the false activation can be shorted in duration. The logic can be expressed as in the following:

$$if \ (\mid \theta_{wda} \mid \ > \Theta_{PLS} \ \ \&\& \ \ \tau_{drive} \leq T)$$
$$\{$$
$$F_{PLS} = 1;$$
$$\}$$

where F_{PLS} is the flag for pre-lift sensing, i.e, $F_{PLS} = 1$ will initiate pre-lift sensing, and τ_{drive} is the drive torque at the interested wheel.

[0075] As is described above, various ways of sensitizing or desensitizing roll control are described. Depending on the various system requirements one, some or all of the ways may be implemented in a commercial embodiment.

[0076] While the invention has been described in connection with one or more embodiments, it should be understood that the invention is not limited to those embodiments. On the contrary, the invention is intended to cover all alternatives, modifications, and equivalents, as may be included within the spirit and scope of the appended claims.